Real-Time Information System Technology Challenges for NASA's Earth Science Enterprise

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Abstract

Future NASA Earth observing satellites will carry high-precision instruments capable of producing large amounts of scientific data. The anticipated networking of these instrument-laden satellites into a web-like array of sensors creates significant challenges in the processing, transmission, storage and distribution of data and data products – the essential elements of what we refer to as "Information Technology". Many of these Information Technology challenges focus on the capability of satellite and ground information systems to function effectively in real time. In future systems, extremely large quantities of data collected by scientific instruments will require the fastest processors, the highest communication channel transfer rates, and the largest data storage capacity to insure that data flows smoothly from the satellite-based instrument to the ground-based archive. Real-time software systems will control all essential processes and play a key role in coordinating the data flow through space-based communication networks. In this paper, we will discuss those critical information technologies for Earth observing satellites that will support the next generation of space-based scientific measurements of planet Earth, and insure that data and data products provided by these systems will be accessible to scientists and the user community in general.

1. Introduction

The National Aeronautics and Space Administration (NASA) has four primary components to its mission: the investigation of space through scientific measurement; human exploration and development of space; aeronautics and space transportation; and the observation and scientific measurement of Earth from space. This last endeavor is the responsibility of the Earth Science Enterprise, which consists of a collection of NASA research centers, academic research laboratories and industry partners, and guided by the Office of Earth Science at NASA Headquarters.

The Earth Science Enterprise studies how our global environment is changing. Using the unique perspective available from space and airborne platforms, NASA acquires, processes and delivers very large volumes of remote sensing and related data to public and governmental entities. These organizations apply this geophysical data and information to understand and solve major problems in the Earth sciences, such as global change, environmental monitoring, agricultural inventory, etc.

The goal of the Earth Science Enterprise is to obtain a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales. Several of the important objectives of the Earth Science Enterprise over the next 20 years includes [1]:

- accurate 14-day weather prediction
- accurate short-range and long-range climate/environmental prediction
- prediction of global air and water quality
- prediction of natural hazards
- efficient management of natural resources

Data necessary to achieve NASA's objectives in Earth science is collected by a wide variety of instruments placed on board current and future satellites. A description of these measurement missions and the instruments they carry is provided on the Earth Science Enterprise home page [2]. The most easily recognizable of NASA's Earth science products are the optical and infrared images produced by LandSat. These images are used in many scientific and industrial applications such as the study of vegetation, crop distribution, continental cloud cover, severe weather, and snow and ice coverage, just to name a few. In addition to images of the Earth, there are many other equally important measurements that provide scientists with a deeper knowledge of the total Earth system and the effects of natural and human-induced changes on the global environment. For example, instruments that measure gravity, atmospheric chemistry (e.g., ozone measurement), solar irradiance, sea and land surface winds, ocean ice, ocean salinity and ocean current are just a few examples. These measurements are made by an assortment of instruments, including laser, radar and radiometric systems that operate over a diverse set of frequency bands to achieve the precision and resolution needed for each measurement.

2. NASA's Approach to Earth Science

NASA's past approach to Earth science focused on placing numerous scientific instruments on relatively large and expensive space platforms. Because of the risk of launch or on-orbit failure, the instruments, spacecraft and space transport system must have multiple redundant components that are built with expensive failure-proof parts. The expense of each mission reduces the number of opportunities to place satellites in space and forces each succeeding platform to become more crowded with instruments. This complicates the system engineering and further drives up the costs. Future spacecraft will need to be smaller with fewer instruments in order to reduce this risk.

The data collected from these instruments is transmitted to the ground, either directly from the earth observing satellite, or relayed through the NASA TDRSS (Tracking Data Relay Satellite System) satellite. The data is then processed to extract certain information products and then archived in a network of storage facilities and made available to the worldwide community of scientists for study. For the most part, NASA is in the business of providing data and data products through measurements taken in space. However, the task of interpreting this data is left to the community of scientists. Some of these scientists work at NASA, but most are in academia, industry and other governmental agencies.

NASA's primary customers are the users of its data. Scientists, working in government, academia and industry, represent perhaps the most important body of users. American scientists have a major voice in the types of space-based measurements that will be planned, and NASA relies on their input for guidance in formulating and implementing satellite missions. Scientists have demanding requirements on the measurements that NASA makes with regard to precision, resolution and the availability of collected data. As the resolution and precision of the measurements increases, so does the volume of data produced by the instruments that make these measurements. This places severe demands on the satellite data processing and transmission system and on the ground storage and distribution systems. A further complicating factor is that scientists prefer to work with uncorrupted raw data. Data that has been pre-processed in any way may distort the underlying information carried by the data and corrupt the information extraction process. From the scientist's perspective, this could potentially make the data unsuitable for present or future use in fundamental earth science research.. Furthermore, data compression techniques that would help relieve the demand on transmission and storage systems are of limited value because these techniques corrupt the raw data in unpredictable ways..

It is clear, for reasons described above, that NASA needs to transition away from large, instrument-jammed observatories to cheaper and lighter space-based platforms. When this occurs, NASA will be able to afford a wider variety of satellite-based measurement systems. These systems will be able to provide significantly better data – in terms of quantity, precision, and resolution – to the science community. Furthermore, if the cost of satellite-based measurement systems can be reduced, more missions can be flown, insuring that the most important data will be collected using the latest instrument technology. These concepts have been under study at NASA over the past several years and have recently been formulated into a visionary concept of the next generation space-based Earth measurement systems, called the Earth Science Vision Initiative [1]. This vision calls for a web-like network of earth observing satellites that collectively monitor the pulse of our planet through a vast array of instruments – a concept referred to as the *sensor-web*. All instruments in the sensor-web can be independently controlled, either by direct command from a user on the ground, or autonomously by the integrated sensor-web system itself. This concept is illustrated in Figure 1.

3. The Challenge of the ES Vision

NASA's Earth Science Vision focuses on the requirements of the world of 2020 and beyond – a world that will demand new and more accurate information about the environment. Measurement approaches will evolve from the current methods - characterizing Earth through individual measurements - to assessing and forecasting the state of the Earth system based on the fusion of multiple, diverse scientific measurements.

The Earth Science Vision is implemented using a flexible architecture consisting of instruments and platforms, and tied together with information systems. As previously mentioned, the concept is often described as a sensor-web – a constellation of small, instrumented satellites, as well as airborne and in-situ instruments, that are networked together into an organic measurement system. In this sensor-web, each satellite is equipped with data processing capabilities that enable it to act autonomously, reacting to significant measurement events on and above the Earth, increasing precision and coverage where needed without human intervention. Signal processing capabilities on board each satellite will give scientists the option of selecting instrument parameters on demand, controlling on-board algorithms to preprocess the data for information extraction. The sensor-web is tied together with high speed optical and radio frequency links, routing user requests to specific instruments, and maximizing the transfer of data to archive facilities on the ground. Data from the sensor-web is merged into assimilation models to make predictions of climate, weather, pollution and natural hazards. The development of these data products via advanced models synthesizes information that can be distributed to a variety of users and applications.

An added advantage of the sensor web is that new technology can be inserted as quickly as it becomes available with no risk to the infrastructure. This provides a standards-based plug-and-play approach to the development of new sensors, measurement platforms and information systems. A result of the smaller, lighter, standardized approach to platforms and instruments is that satellites in this sensor web can be designed for shorter operational lifetimes than today's large systems. This keeps the instrument technology in space closer to the state-of-the-art, and insures that the data collected represents the best science is able to provide.

Significant advances in technology are required to bring about this vision. Most notably, information technology driven by real-time software systems will be a key element in integrating all of the component parts of the sensor web and completing the flow of data from collection and transmission, to information extraction and distribution. A complete path from the instrument to the user, and information systems operating under real-time constraints will make it a reality.

4. The Role of Information Technology

Real time systems will play a crucial role in bringing the Earth Science Vision into reality. New scientific instruments will swell the volume of data flow from terabytes (2 to the 40^{th} power) to petabytes (2 to the 50^{th} power) and beyond. These large volumes of data will need to be processed, transferred, and stored in real time. Information technology will be required to tie together the sensor-web into a viable network of instruments capable of functioning autonomously, yet responding to independent requests from users. Fast processors and high speed data links will be required to route the data to its destination without congesting the data paths.

Consider the following scenario: A constellation of earth observing (EO) satellites are distributed in orbits ranging from 200 km to geostationary and beyond. Several sentinel satellites are placed in geostationary orbit and spaced to provide a line-of-sight view of all instrumented satellites in the constellation. Through GPS positioning, the sentinel satellite knows the precise location of all members of the constellation, this information having been communicated to the sentinel from all satellites through low-rate communication links. Each EO satellite is a small, lightweight and relatively inexpensive platform hosting several instruments. As one satellite in this constellation – a synthetic aperture radar satellite in low Earth orbit – passes over a remote part of the world, on-board sensors detect a volcanic event. The autonomous satellite rotates its instruments into position and alters its coverage area, adjusting system parameters in order to bring the event into focus. After data collection and SAR processing is complete, on-board feature detectors analyze the data and assigns priority levels to different parts of the image. The initial image contains 4096x4096 pixels with a precision of 8-bits per pixel, which produces over 16 Megabytes of data. A progressive data compression scheme processes the data and prepares it for transmission to the ground. However, since the remote sensing satellite is out of view of a communications ground station, it locates another member of the constellation – a satellite in a higher orbit carrying an instrument to measure atmospheric chemistry – that is currently in view of a ground station and can establish ground connectivity. (An alternative scenario may have the sensor transmit data back to the sentinel for relay to the ground.) Since the satellites are in different orbits, their relative velocities vary significantly. In spite of this highly dynamic scenario, both satellites must establish and maintain a high-speed data link. The SAR satellite commands its optical communication system to establish a crosslink with a higher orbiting satellite and tracks that satellite while the data is sent through it to the ground. The SAR satellite transmits the image in a course to fine manner with the more important parts of the data first sent back at higher resolution then followed by the less important parts of the data. Scientists at academic and governmental research centers are alerted to the event and, through a coordinated effort, assume control of the spacecraft and direct its instruments for specific follow-up measurements.

This scenario provides a snapshot of the Earth Science Vision concept and illustrates how the sensor-web approach will facilitate better access to scientific knowledge. Clearly, information technology and real-time information systems tie the sensor-web together and provide a degree of access to space-based instrument data that currently does not exist. Data collection technologies, high speed digital processors and components, optical and RF data links, network protocols and storage technologies form the core information technology challenges for realizing the Earth Science Vision. These challenges are discussed further in the following section.

5. Information Technology Challenges

Information system technology challenges can be broadly classified into categories relating to satellite on-board functions, ground-based activities and the requirement to link these systems together into a single organic unit. Long range planning is required for technologies needed to bring the Earth science vision into reality. Over the next decade, NASA will be investing in a variety of research efforts that will enable these challenges to be met. Several interesting information technology challenges and their constituent technologies are described in the paragraphs that follow.

5.1 On-Board Processing and Intelligent Sensor Control

The challenge of on-board data processing and intelligent sensor control relies on technologies that support the configuration of sensors, satellites, and sensor webs of space based resources. Examples include capabilities which allow the reconfiguration or retargeting of sensors in response to user demand or significant events. Also included in this category are on-board processing of sensor data through the use of high performance processing architectures and reconfigurable computing environments, as well as technologies that support or enable the generation of data products for direct distribution to users.

Today's Earth observing satellites collect and downlink data without the benefit of on-board processing. Future systems will have sophisticated on-board processing capabilities that will be made possible by advances in processor technology, software systems and algorithms. On-board processing will be applied several critical satellite and instrument functions. One of the essential capabilities provided by on board processing is autonomy. Autonomous data collection allows smart instruments to adjust their data collection scheme configuration in order to optimize a specific measurement.

Another capability provided by on-board processing will involve data acquisition, information extraction and data compression. One of the key advantages of on-board processing will be the ability to determine what data to compress, including whether some data could be ignored or reduced. This will be critical to successful handling of high volumes of data. It may be infeasible, or indeed undesirable, to archive every bit of raw data collected from an instrument. Therefore, some form of data reduction or information extraction may be required. Data reduction from space based systems to ground will require feature extraction technologies based on semantic content and other characterization. Traditionally, scientists have not been willing to part with any data, either by reducing data fidelity with lossy compression or by discarding raw data after it has been processed. Algorithms are constantly being refined, new algorithms are being developed and new applications for data continue to arise. However, the time will come when space based measurements can be executed on demand and the requirement to archive every byte of data is neither practical nor desirable.

Since the on-board processor must service signal processing (arithmetic manipulation of the collected signal) and data processing (storing, routing and execution of command and administrative data) functions, an important requirement for the processor is that it be reconfigurable. Device technologies that allow a processor and its supporting components to function in several different roles will be especially valuable. Reconfigurable processors, or adaptive computers, have their configurations changed as the environment in which they are operating changes, as mission requirements evolve, and as algorithms are modified or replaced. This would greatly enhance a system's flexibility and performance over the lifetime of a mission

5.2 Intelligent Platform Control

The challenge of intelligent platform control requires technologies that enhance the intelligence and autonomy of on-board sytems, including improved spacecraft telemetry and navigation. Examples include agents for autonomous operations for single spacecraft and for sensor webs, and supporting capabilities such as decision support tools, planners, and high level command protocols based on science objectives

Autonomous spacecraft control allows platforms to adjust their positions in space relative to the constellation of sensors in response to new science opportunities and collaborative data gathering. Autonomy can be achieved by a variety of approaches. For example, remote agents, goal directed closed loop commanding, model based reasoning, on board deduction and search, high level commanding, proactive and reactive planning, and machine learning are candidate techniques for achieving autonomy.

5.3 High Data Transmission and Network Configuration

The challenge of high data rate transmission and network configuration requires technologies that support the transfer of data through high speed wireless (optical or RF) data links connecting satellite to satellite, or satellite to ground including innovations in intelligent communications. Examples include network infrastructure, together with protocols and standards, that integrate the system of sensors into a web.

The weakest link in the data flow is the free space wireless connection between satellites and between satellite and ground. Furthermore, the greatest challenge will be establishing and maintaining a viable communication network among a constellation of satellites operating in diverse orbits. It is anticipated that the demand for increased throughput will increase at a greater rate than available bandwidth, regardless of the transmission technology used. Optical data links above the Earth's atmosphere will tie the constellation together into a functioning web-like structure. This is not a simple problem due to the relative velocities of the component satellites in the constellation. High speed networks in space may require each satellite to track one or more other satellites in the constellation for the purpose of maintaining a viable network structure

Protocols such as *IP in the sky*, can support an on board internet using commercially compatible standards (e.g., ATM, IP) which will provide connectivity from scientist to instrument (end to end) and for distributed information systems in space. Intelligent communications networks involving artificial intelligence, protocols, and network management are vital elements supporting the dynamic nature of space operations networks. Sensor-webs, satellite constellations, and ground gateways will function together to extend the Internet to space.

Finally, other technologies that increase data transmission throughput that will play an important role in implementing high speed data links are new bandwidth and power efficient modulation and coding techniques, high performance electronically steered antenna systems, and adaptive / configurable network and radio architectures.

5.4 Data and Information Production, Distribution and Storage

The challenge of data and information production, distribution and storage requires technologies that support the storage, handling, analysis and interpretation of data. Examples include innovations in the enhancement, classification or feature extraction processes. Also included are data mining, intelligent agent applications for tracking data, distributed heterogeneous frameworks (including open system interfaces and protocols), and data and/or metadata structures to support autonomous data handling.

Storage technology will continue to evolve allowing greater volumes of Earth science data to be archived – perhaps even in space. In order to access data in an efficient manner, advanced database technologies will be required. Data warehouse and on-line analysis processing technologies will be especially valuable for certain classes of data. On board storage technologies will need to be high density, radiation hardened and have a fast record and access rate. These devices may involve holographic or other optical storage mechanisms.

In order to make the data and data products useful to a broad class of users, software technologies that simplify the manipulation of data will be needed, such as feature extraction/change detection, and algorithms that permit dynamic interaction and human-centric interaction. Feature extraction, change detection and theme identification will enhance the speed of processing, thereby reducing the volume and increase the relevance of data for Earth science research. Dynamic interaction will allow accelerated access to data by enhancing searching, collection and cataloging of Earth science data. Human centric interaction is the key in easing access to scientific data, algorithms and products by presentation and visualization of data products in a form easily recognizable, interpretable or manipulable by a human being.

6. Summary

The next generation of Earth observing satellites will use instruments based on technologies that provide Earth science measurements to a degree of precision and span of coverage not currently available. However the most compelling characteristic of these satellites may be the ease with which users have access to the collected data, directly from space. This is the concept of the sensor-web – a closely integrated constellation of measurement satellites that can act autonomously in controlling instruments and spacecraft, while also responding immediately to the commands of the user interested in specific measurements. The key to this vision is the real-time information systems which are required to solve the grand challenges associated with on-board processing and intelligent sensor control, high data rate transmission and network control, intelligent platform control, and information production, distribution and storage

References

1. Earth Science Vision Initiative, available for viewing at *http://staac.gsfc.nasa.gov/esv.htm*

2. The Earth Science Enterprise Strategic Plan. Available for viewing at *http://www.earth.nasa.gov/visions/stratplan/index.html*.

3. The NASA Information Systems Technology Program can be reviewed at *http://esto.gsfc.nasa.gov/programs/aist.html*

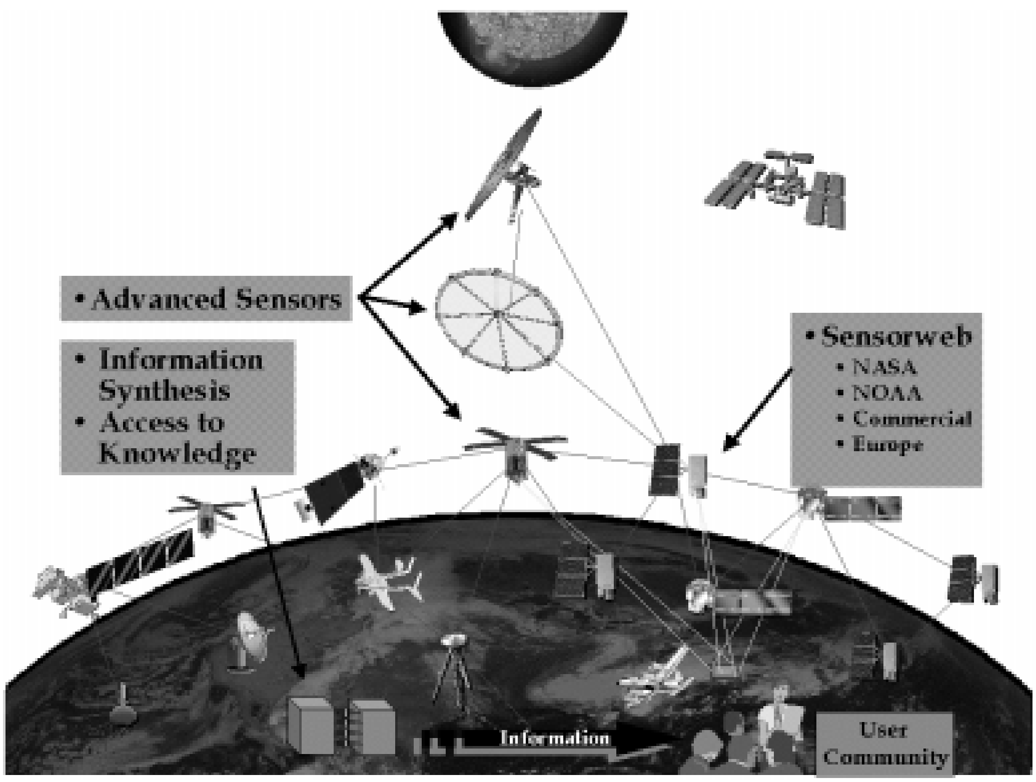

Figure 1 – Earth Science Vision Conce